Power Management for an Electrified Bus

UNDERGRADUATE HONORS THESIS

Presented in Partial Fulfillment of the Requirements for Graduation with
Distinction in Mechanical Engineering

By

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ABSTRACT

Transit buses are the most important form of public transportation, and there is a continuing effort to make them more fuel efficient to reduce their economic and environmental footprint. One means of improving the fuel economy of buses is by replacing fuel consumed to power the vehicle and its accessory loads with electricity. This can be accomplished by way of hybrid powertrains (hybrid-electric buses are a common sight today), and by managing the accessory loads in a more efficient manner. The focus of the research carried out in this project pertains to the increasing electrification of buses. This electrification has created a high demand for additional electrical energy to power accessory loads such as air conditioning, and air compressors. Conventional buses use multiple alternators to supply the additional energy. In this project we explore the possibility of using a single, larger electrical generator and an optimal power management strategy to service the accessory loads more efficiently. An important step in the process of developing a power management strategy is to develop efficiency models of each of the subsystems to be managed. Efficiency models are developed to understand the power consumption of fans, air conditioners, air compressors, and power steering pumps, and these models are incorporated into a computational model that includes the engine and all of its loads. The mathematical and

computational models developed will make it possible to increase the overall efficiency of a bus by enabling the design of optimal power management strategies. Results of simulations show that while there isn't a difference in fuel economy between a conventional and electrified bus, adding regenerative breaking can increase fuel economy by 13%. Buses are high mileage vehicles, so increases in fuel efficiency are extremely important and make large differences in the amount of fuel used. This reduces the economic and environmental impact of buses.

ACKNOWLEDGEMENTS

First, I would like to thank my advisor, Giorgio Rizzoni. He not only guided me through this entire process, answering any and every question I had, but also used his connections to help me find a job this summer.

I would also like to thank Qadeer Ahmed, who spent hours looking at Matlab code and Simulink diagrams with me, even taking time out of his day on a Sunday to help me. Without him, I would never have solved many of the problems I faced with the simulator.

Finally, I would like to thank Lorenzo Serrao, although I have never met him. The simulator he built during his time at Ohio State saved me countless hours of modeling, and the detail level in his simulator manual allowed me to understand how it operated without spending an excessive amount of time staring at a computer screen.

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CHAPTER 1: INTRODUCTION

1.1 Motivation

In today's world, more and more energy consuming devices are being built every day. While these devices may be deemed energy efficient, more people using more devices leads to more energy being consumed. A graph of the world energy consumption from 1990-2040 is shown in Figure 1.

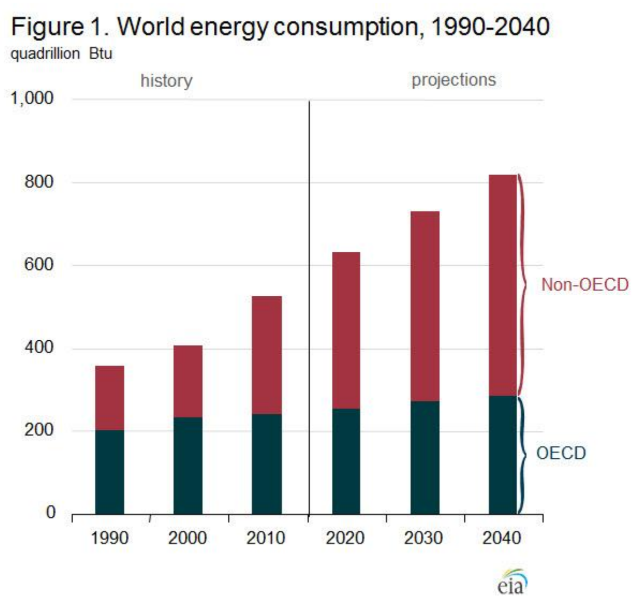

Figure 1- World Energy Consumption [1]

The world energy consumption is projected to increase by 200 quadrillion Btu over the next 30 years, which is more than a 30% increase. Much of this increase will be seen in regions that are non-OECD, however some growth will still be seen in OECD regions. The increasing demand for energy calls for an increase in efficiency as a counterbalance. The U.S. energy consumption by source and sector is shown in Figure 2.

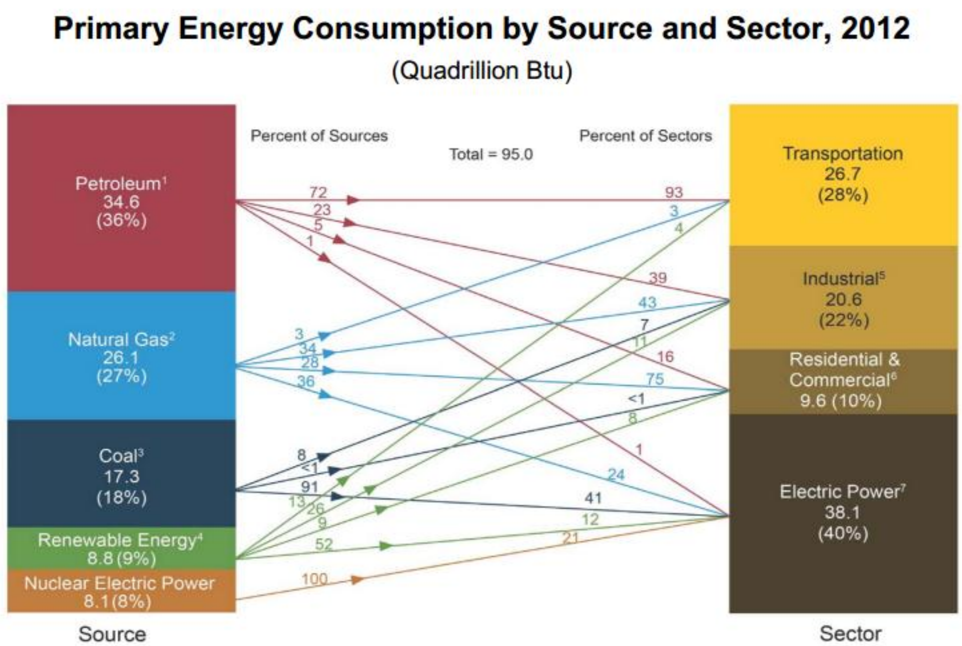

Figure 2- Energy Flow Trends [2]

The energy consumption by sector shows that 26.7% of the energy consumed in the U.S. is used for transportation purposes. Of this 26.7%, 93% comes from petroleum, while 3% comes from natural gas and 4% comes from renewable energy sources. This shows that the majority of the energy used for transportation isn't renewable and provides a large potential for an increase in overall efficiency. Public transportation can be used to increase the overall efficiency of the transportation sector and overall energy use. The passenger miles traveled over different modes of transportation is shown in Figure 3.

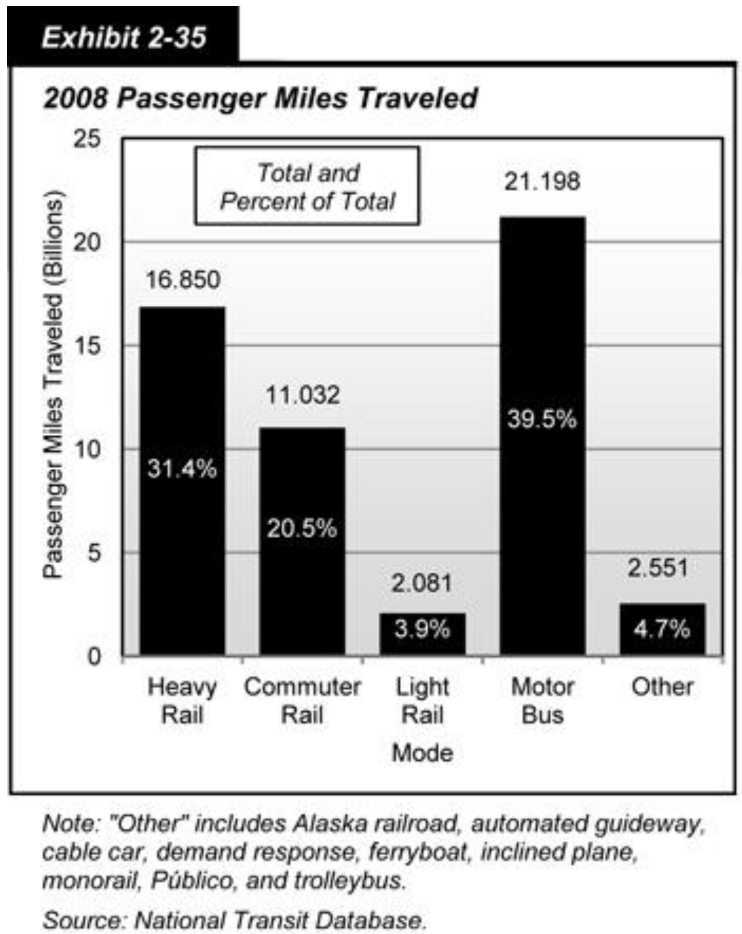

Figure 3- Passenger Miles Traveled [3]

A passenger mile traveled is the sum of the total miles traveled by each individual passenger on each mode of transportation. For instance, one person traveling forty miles on a bus is the same as forty people traveling one mile on a bus. Motor buses travel approximately 21.2 billion passenger miles, which is 39.5% of the total passenger miles traveled. This shows the high degree of utilization for buses in today's society, and provides motivation to increase fuel economy.

1.2 Background Research

Hybrid-electric buses are a common sight today. An example of a transmission-based hybrid system manufactured by Eaton is shown in Figure 4.

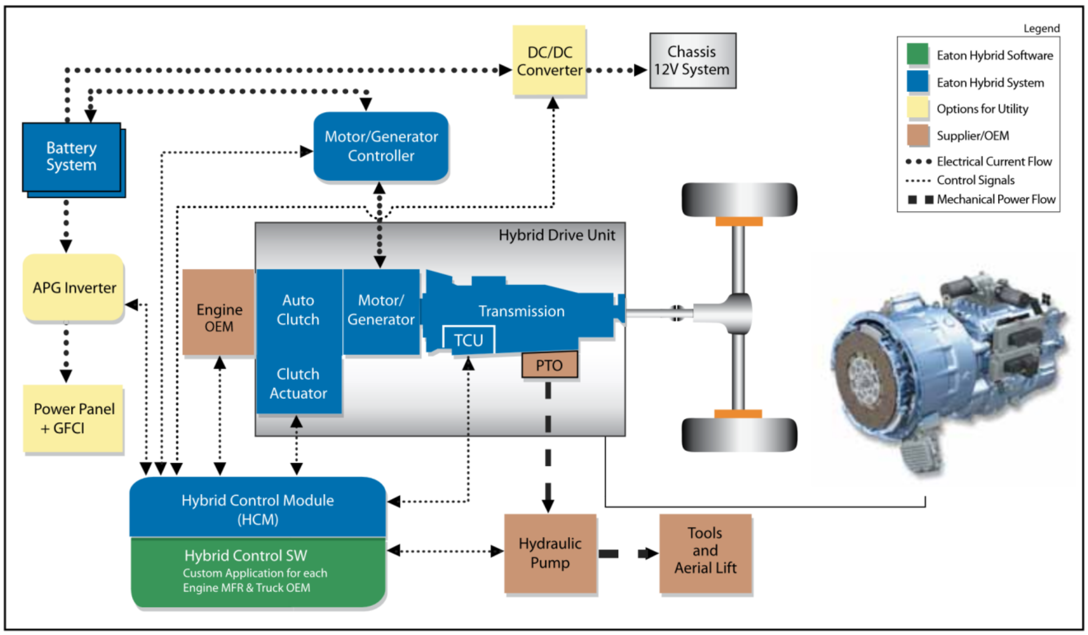

Figure 4- Transmission-Based Hybrid [4]

The hybrid drive unit can be purchased by a bus manufacturer in order to convert an otherwise conventional bus into a hybrid-electric vehicle. The hybrid-drive unit consists of the transmission, a motor generator, a clutch to connect to the engine, a battery pack, the control module, and the hybrid control software. The engine and other accessories are purchased by the bus manufacturer from other suppliers, and can be seen in brown in Figure 4. Since the hybrid unit can be purchased in place of a conventional transmission, the unit can be fitted onto a conventional bus to transform it into a hybrid-electric bus. The auto clutch is an automated clutch that connects the engine to the electric machine. The electric machine is then attached to the transmission, and then to the wheels. If the clutch disengages, the engine can be turned off and the vehicle can be run entirely on electrical power, or the engine can be turned on and the clutch closed to run with a combination of electrical and mechanical power.

Transmission based hybrid buses can reduce emissions by up to 65% and increase fuel economy by up to 65% [5]. However, the costs of these transmission based systems can cause the bus to cost between $450,000 and $550,000, compared to about $290,000 for a conventional bus [6]. This 55% to 90% increase in cost prevents transmission-based hybrid buses from being a financially attractive option to potential customers.

An engine-based hybrid-electric bus manufactured by BAE Systems is shown in Figure 5.

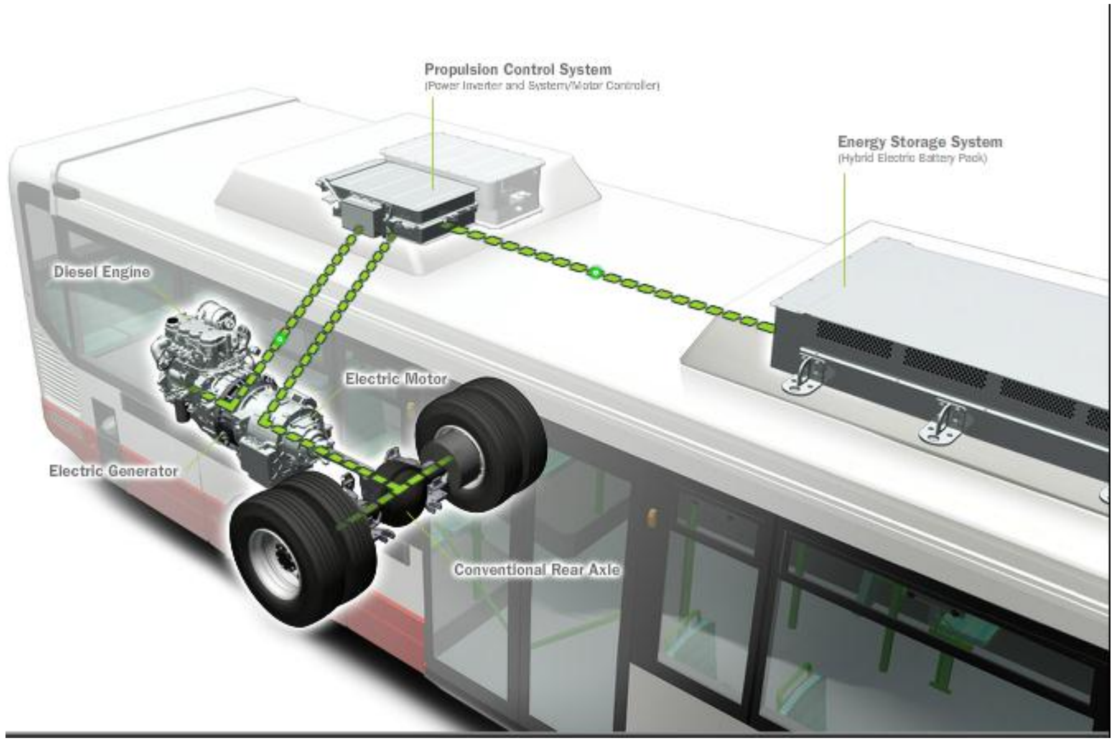

Figure 5- Engine Based Hybrid Electric Bus [7]

This engine based hybrid bus operates in series configuration. This means that the diesel engine is connected to an electric generator and acts solely to generate electricity for the traction motor. There is a battery pack that stores excess electric energy, which allows the diesel engine to turn off when additional energy isn't needed. An electric machine is attached to the rear axle of the bus, and this electric machine acts as the only source to power the wheels. It can also act as a generator when used during braking to regenerate electrical energy. This engine-based hybrid bus can increase fuel economy by up to 30%, yet it costs $385,000 [8]. Therefore, a 33% increase in cost of the vehicle yields a 30% increase in fuel savings.

1.3 Overview of Thesis

This thesis provides an overview on power management for an electrified bus. Chapter 2 discusses the powertrain architecture that will be used throughout this thesis and defines the project objectives. Chapter three presents the models of accessories that were used during the simulations. Chapter 4 discusses the vehicle simulator and the results of the simulations. The conclusions are presented in Chapter 5.

CHAPTER 2: PROJECT BACKGROUND

2.1 Powertrain Architecture

The powertrain architecture for this project was supplied by Cummins Inc. A diagram of the architecture is shown in Figure 6.

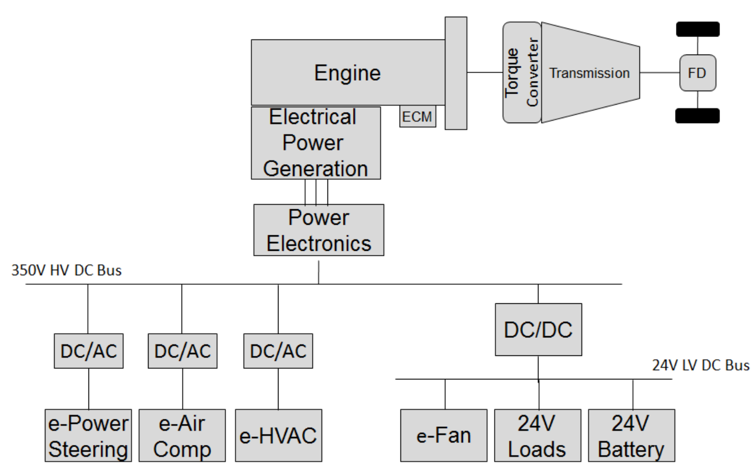

Figure 6- Powertrain Architecture

The drive wheels are attached to an automatic transmission and torque converter, which is identical to a conventional bus powertrain. The engine is attached to the torque converter, and for the purpose of this specific powertrain, supplies all of the power to the wheels. The integrated alternator is mechanically coupled to the engine through a gear train. The alternator takes power from the wheels and engine and converts it to electricity. The power electronics serve the purpose of regulating the alternating current of the alternator and converting it into a constant direct current energy source for the high voltage bus. Then, a series of smaller inverters convert the direct current energy back into alternating current for the power steering, air compressor, and HVAC (heating, ventilation, and air conditioning) to use. A DC/DC converter then steps down the voltage to accommodate a low voltage bus, where the fan and other 24 volt loads will connect, as well as a 24 volt battery.

Advantages of this powertrain as opposed to traditional hybrid powertrains (where both the electric motor and internal combustion engine power the wheels) lie in the smaller impact of the electronics on the overall system. A smaller battery will decrease the cost of the system, as compared to a traction based hybrid with a larger battery. The system also requires a smaller electric machine and other power electronics, because the system only has to supply power to various accessories, instead of powering traction motors that supply power to the wheels.

2.2 Project Objectives

A set of project objectives was defined by Cummins Inc. and the project team at Ohio State at the start of the project. This project will expand beyond this thesis, so not all of these objectives will be addressed in the body of this thesis. The first objective was to develop accessory models to be used during the simulations. These models will be modeled using a combination of energy and physics-based modeling. Energy based modeling focuses on the power consumption of the accessories at various operating conditions during the simulations. Physics-based modeling focuses on dynamics and the physical responses of the system. The next objective is to develop or adapt a current vehicle simulator into a simulator of a bus for this project.

The final objective is to develop a control strategy based on optimal principles. Load management during idle and derates must be developed. Under these conditions, the engine power is severely limited, so a strategy must be determined in order to manage accessories with limited electrical power. Transient load management (when accessories turn on) will provide a challenge because accessories draw more current when turning on. A strategy for regenerative braking must also be determined. Since the battery in the system is low voltage, it limits the possible energy storage capacity in the battery. This provides a challenge for the regenerative braking, because the battery cannot necessarily accept all of the energy from regenerative braking. Therefore, when additional electrical energy is present, there needs to be a way to store it. Methods to do this include storing air in tanks by using the air compressor, cooling the engine using the fan, or using the HVAC unit to cool the cabin down.

2.3 Project Methods

The methods involved with completing this project were to develop energy models of accessories. These models were created by obtaining data that related the input speed of accessories to the torque demand of the accessory at the given speed. Since speed was the model input and torque was the output, the power demand of the accessory was known. These models were then implemented in Simulink. A simulator of a garbage truck was then modified to eliminate excess loads and parameters were changed to be consistent with that of a transit bus. After the parameters were implemented in the simulator, the vehicle was run over a single Manhattan cycle. Finally, the power consumption of the vehicle and the accessories were analyzed.

CHAPTER 3: ACCESSORIES

3.1 Functional Analysis of Accessories

This section overviews how each accessory operates.

Alternator

The integrated alternator provides the power for the entire electrical system. The electric machine used in this system is a permanent magnet synchronous generator. A diagram of a permanent magnet synchronous generator is shown in Figure 7.

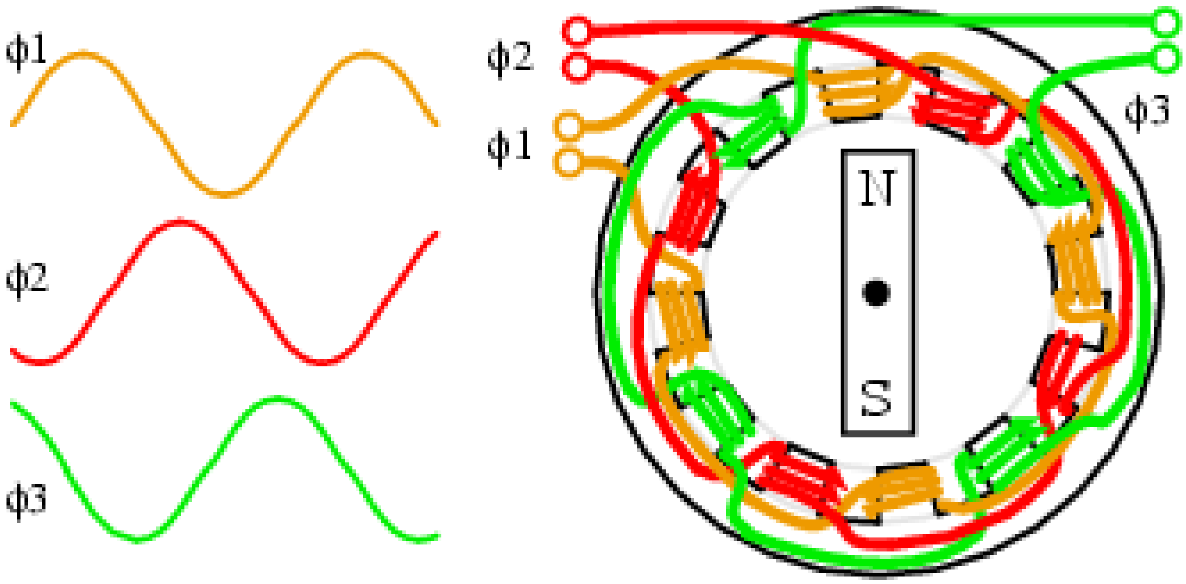

Figure 7- Permanent Magnet Synchronous Generator

A permanent magnet is mounted on the inside rotor, and three phase windings are wound on the outside stator. If a mechanical force causes the rotor to rotate, the rotating magnetic field then excites the windings and produces a three phase alternating current throughout the stator, with the frequency of the alternating current corresponding to the speed of the rotation. The reverse reaction can also occur, where a voltage can be applied across the windings to cause the rotor to rotate, however the electric machine will only be used as a generator and not a These principles can be used to generate electrical energy to power accessories or to be stored in the battery for later use.

Fan

Fans are comprised of an electric motor attached to a set of blades that rotate and cause airflow in a certain direction. This air is then used to cool the engine's water jacket or charged air cooler. The fan used in the system is a Mini-Hybrid third generation fan produced by EMP, shown in Figure 8.

Figure 8- EMP MINI-HYBRID GenIII

The electric fan consists of nine smaller fans, and they work together to cool down the engine. There are multiple settings that the fan operates at, based on the engine temperature. As the temperature rises, the fan speed and power draw increases in an attempt to cool the engine down faster.

Air Compressor

The air compressor used with this powertrain architecture is a reciprocating, piston based air compressor, driven by an electric motor, as shown in Figure 9.

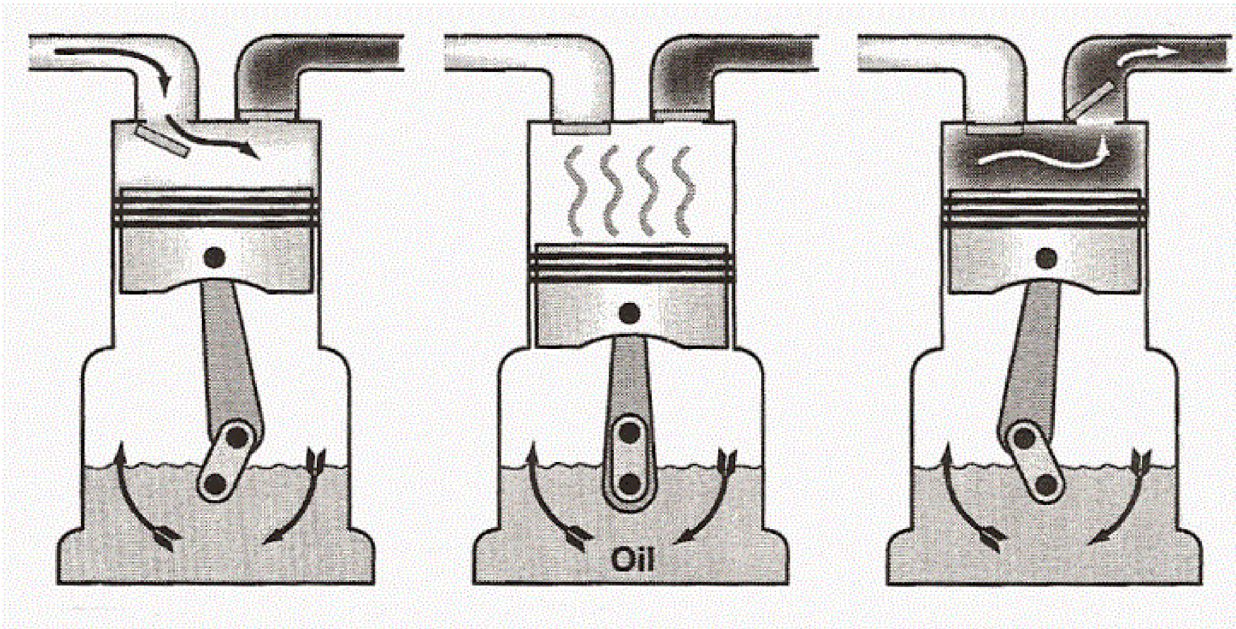

Figure 9- Air Compressor [13]

An electric motor causes the rotation of the shaft and the motion of the piston. Air enters the cylinder as the piston moves toward bottom dead center. In this step of compression, the volume in the cylinder is increasing as the pressure drops to its lowest value during the cycle. Once the piston reaches bottom dead center, the intake valve closes and the piston moves upward, toward top dead center. The volume in the cylinder decreases as the pressure rises to its highest value. This compresses the air, which is then released into a pressurized tank. The compressed air can then be used to operate accessories like air brakes.

Power Steering

The power steering unit used in this powertrain is electro-hydraulic, meaning that an electric motor controls the hydraulic pump and causes it to rotate.

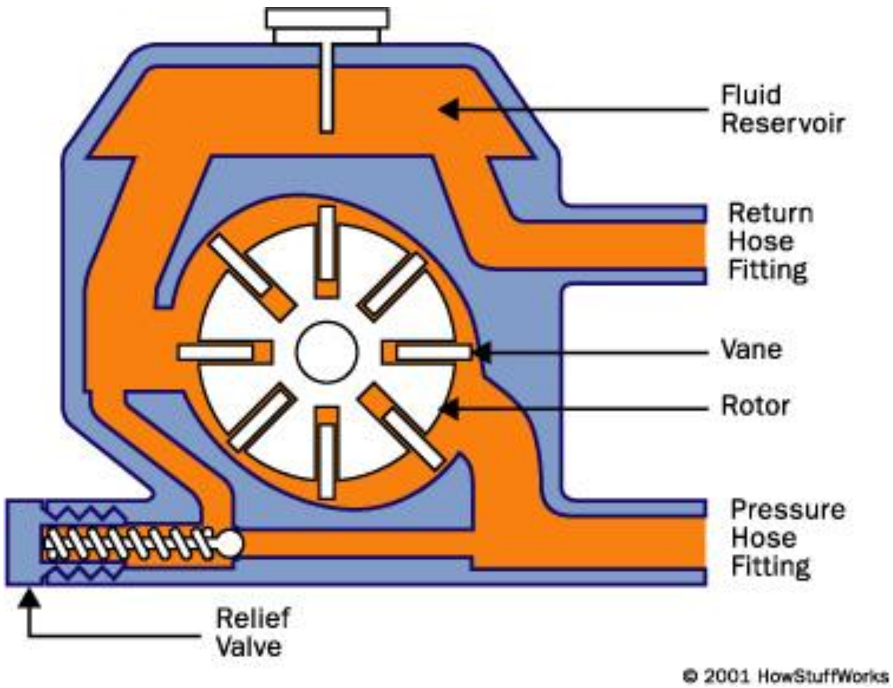

Figure 10- Power Steering Hydraulic Pump [12]

Low pressure hydraulic fluid enters the chamber with the rotor. The vanes are used as actuators to cause rotation in the rotor, which forces the oil into pockets between the chamber and the rotor. These chambers pressurize the oil and force it into the fluid reservoir. The pressurized fluid is then used to power the power steering unit by actuating valves and causing motion in the steering rack. Since the valve consumes fluid power produced by the motor, only the hydraulic motor consumes power directly from the electrical generator.

HVAC

Any heating, ventilation, and air conditioning (HVAC) system operates off of a vapor compression cycle, shown in Figure 11.

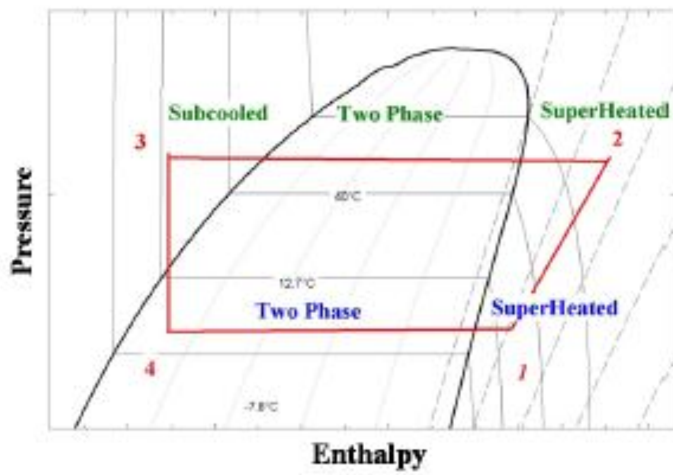

Figure 11- Vapor Compression Cycle for an HVAC [14]

The cycle starts at phase one, with high enthalpy, superheated, low pressure vapor. Then the vapor is compressed to phase two, before moving at a constant pressure to the sub-cooled, low enthalpy region at phase three. Then the refrigerant moves into the two phase region at a low enthalpy and pressure before being compressed and starting the cycle again. A diagram of an automotive HVAC system that shows how each step in the phase cycle occurs can be seen in Figure 12.

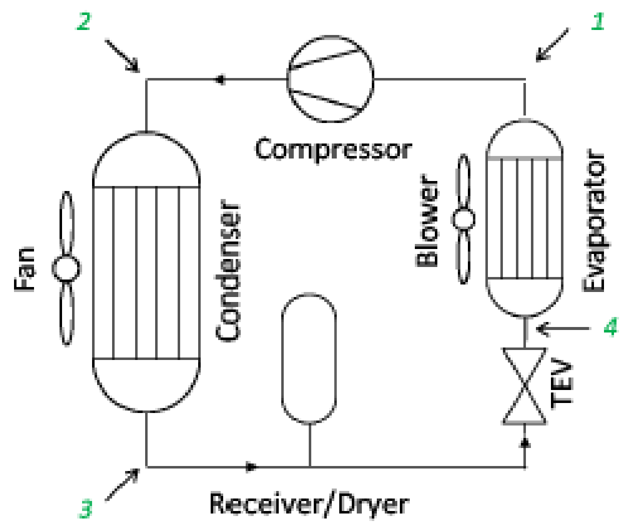

Figure 12- HVAC Diagram

A fixed displacement piston compressor, fan, and blower are powered by electric motors. The compressor compresses the refrigerant, which increases the pressure. The refrigerant passes through the condenser and the dryer, which decreases the enthalpy of the fluid. The fan forces air through the condenser, which removes heat from the refrigerant. The refrigerant decreases pressure as it travels through the valve, and then cools the cabin by accepting heat through the evaporator.

Power Electronics

There are two different types of power electronics in the system. A DC/DC converter transfers energy from the high voltage bus to the low voltage bus so that the low voltage loads and battery can connect to the system. The second type of power electronics is an inverter, which takes the direct current energy at the high voltage bus and turns it into alternating current energy.

DC/DC converters either increase or decrease the voltage between the input and output while conserving power, minus small losses due to the efficiency of the converter. Typically, DC/DC converters use a magnetic field to transfer power, using either a transducer or an inductor. The magnetic field transforms power from one side of the circuit to the other, but either steps the voltage up or down, depending on the application. In the case of the bus, the DC/DC converter steps the voltage down, and since the power is held relatively constant, the current that can be drawn out of the low voltage bus is larger, proportionally to the step down in voltage.

AC/DC converters, or inverters, convert a direct current power source to an alternating current power source by using a series of switches. These switches turn on and off very rapidly in a sequence that produces a square wave, which can be turned into a modified sign wave with more switches and filters. A description of this is shown in Figure 13.

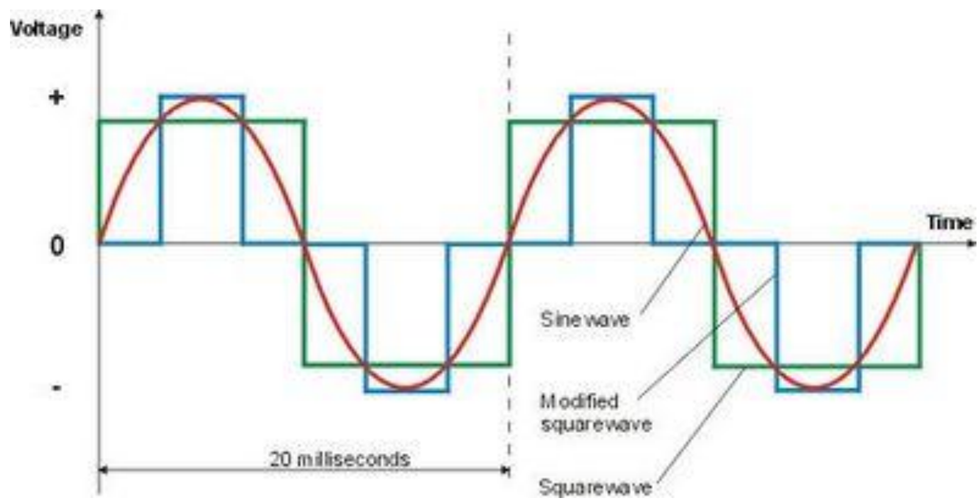

Figure 13- Square Wave to a Sin Wave

The series of square waves can resemble something similar to a sine wave. The square wave can be further refined with more switches to produce more steps, however, there will still be vertical sections in the wave. This is undesirable, because the change in derivative of the voltage response is near infinite, so filters can be added to smooth the function out. With enough filtering, the waveform can resemble a near perfect sine wave.

An inverter also regulates the energy produced by the electrical generator. However, instead of taking a constant DC current and changing it to AC current, this inverter takes current that is always changing, because the electric generator is directly attached to the engine. This inverter must regulate this current and change it to DC current to be used on the high voltage bus.

3.2 Energy Modeling of Accessories

All of the accessories are modeled using the same black box model, shown in Figure 14.

Figure 14- Accessory Black Box Model

All of the accessory models receive an input speed and a duty cycle signal. The input speed determines the torque demand of the accessory. Since the input speed is the input and the torque demand is the output, the power consumption of the accessory can be determined, as shown in Equation 1.

$$P = T\omega \qquad [1]$$

Where:

P= Power consumed by accessory (w)

T= Torque demand of accessory (T)

ω= Rotational input speed to accessory (rad/s)

The input speed of the accessory models is equal to the engine speed for a conventional bus. This constrains the every variable in the model, eliminating any possible control strategy for conventional accessories, with the exception of the duty cycle. However, for a bus with electrified accessories, the input speed to the accessories is determined by the electronic motors connected to each of the accessories. This allows each accessory to function independently from the engine and each other. The speed of the electrified accessories was determined by comparing the energy consumed by the conventional accessories and having this number be similar to the energy consumed by the electrified accessories over a Manhattan cycle.

The duty cycle of each accessory determines whether the accessory is on or off. Each of the accessories use different duty cycles, which were taken from a previous simulator [9]. These duty cycles determine the amount of energy consumed by each accessory, and the duty cycle remains unchanged between all of the simulations.

The torque demand of each accessory is determined from Equation 2.

$$T = \frac{1}{\eta}\frac{P}{\omega} \qquad [2]$$

Where:

η= Efficiency of the accessory

These values are determined by look up tables that determine the torque demand of the accessory from the input speed.

Each electrified accessory is powered by an electric motor that produces the rotational energy that the accessory consumes. For the purpose of this thesis, these electric actuators are modeled as ideal, meaning all of the electrical energy they consume is converted into mechanical energy for the accessories to use.

Fan

The power consumption of the fan is determined by the speed of the fan. Since the fan that is being used is electric, the speed of the fan determines the amount of current that the fan consumes at a rated voltage of 24 volts. The power consumed by the fan can be expressed as a product of the current and the voltage, as shown in Equation 3.

$$P = IV \qquad [3]$$

Where:

I= Current (A)

V= Voltage (V)

Once the power consumption of the fan is determined, it can be converted into a mechanical torque using Equation 1. This allows the fan to be run off the engine and demand a torque from the engine for the conventional bus simulations. The current drawn from the fan at given speeds is shown in Table 1.

Table 1- Current Drawn to Power Fan at Rated Speeds [15]

Speed (RPM)	Current (A)
0	0
750	3
1812	14
2875	36
3938	80
5000	160
5500	204

The torque versus speed response for the fan is shown in Figure 15.

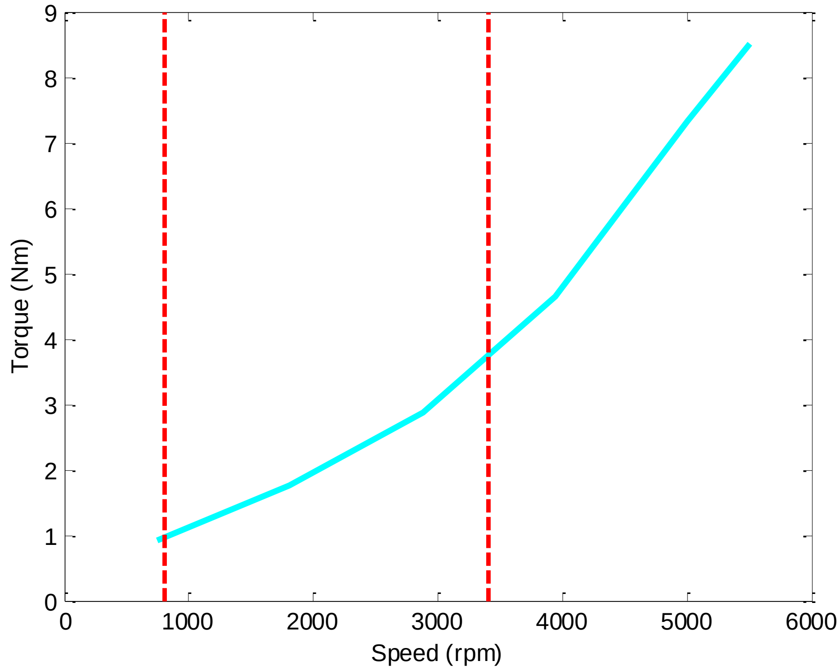

Figure 15- Fan Torque Demand vs Operational Speed

The red lines show the operating condition of the engine, with the idle speed at 800 rpm and the maximum speed during a Manhattan cycle of around 3300 rpm. The torque demand of the fan increases quadratically with respect to speed. This is an expected response, because the force applied on a body by air resistance scales quadratically with velocity.

The fan controls the temperature of the radiator and the engine, however, a reasonable accurate thermal model of the engine must be developed in order to determine an accurate temperature of the vehicle. Without a thermal model of the engine, the duty cycle of the fan can be used to simulate the amount of time that the fan needs to be on in order to provide adequate cooling for the engine.

Air Compressor

The power consumption and therefor torque demand of the air compressor is determined by the input speed. The torque demand at a given speed of the air compressor is shown in Figure 16.

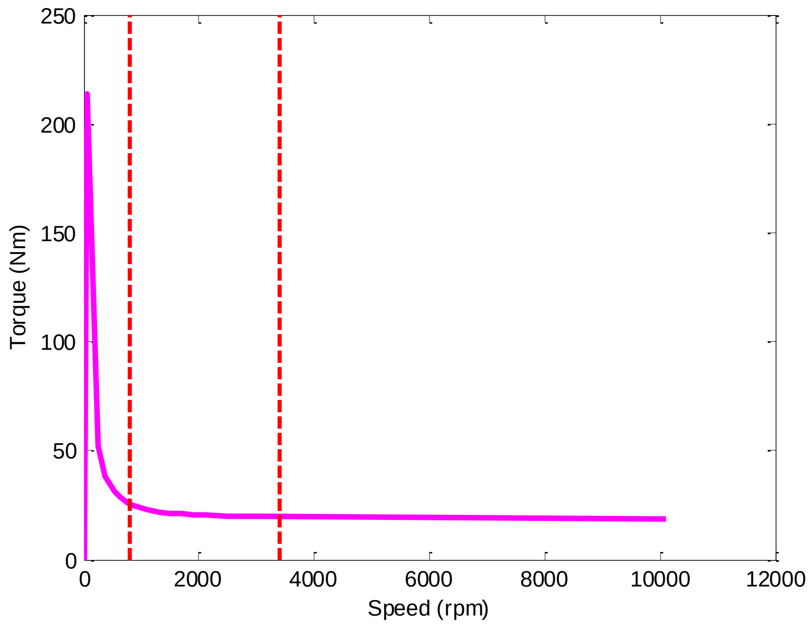

Figure 16- Air Compressor Torque Demand [9]

The air compressor model uses lookup tables with data from a garbage truck simulator, where the data was originally provided by Cummins Inc. [9]. The torque demand of the air compressor is a fairly constant value across the operating speeds of the engine. It requires a high amount of torque at very low speeds, and then decreases to a constant value. This means that the power demanded by the air compressor scales with the input speed, Equation 1, and the fact that the torque request is approximately constant. The spike in torque demanded by the air compressor at very low speeds is most likely attributed to the high amounts of friction that occurs when the piston speed is very slow.

The air compressor puts compressed air into a tank with a constant volume. The air compressor maintains the pressure in the tank, however, without modeling how the compressed air is used on the vehicle, the pressure in the tank wouldn't decrease. Therefore, the air compressor duty cycle estimates how often the pressure in the tank needs to be replenished, and the air compressor turns on accordingly.

Power Steering

The model for the power steering unit only contains the power steering pump, and not the entire power steering assembly. This is because the assembly that controls the power steering consumes the energy in the hydraulic fluid, and without modeling how steering impacts the pressure in the reservoir or determining the amount of steering in a drive cycle, this is impossible. However, this power consumption can be modeled as part of the duty cycle input, where the duty cycle determines how often a power steering pump would turn on over a given cycle. The more energy that the power steering assembly consumes, the more often the power steering pump has to turn on. The torque demand of the power steering pump at different input speeds is shown in Figure 17.

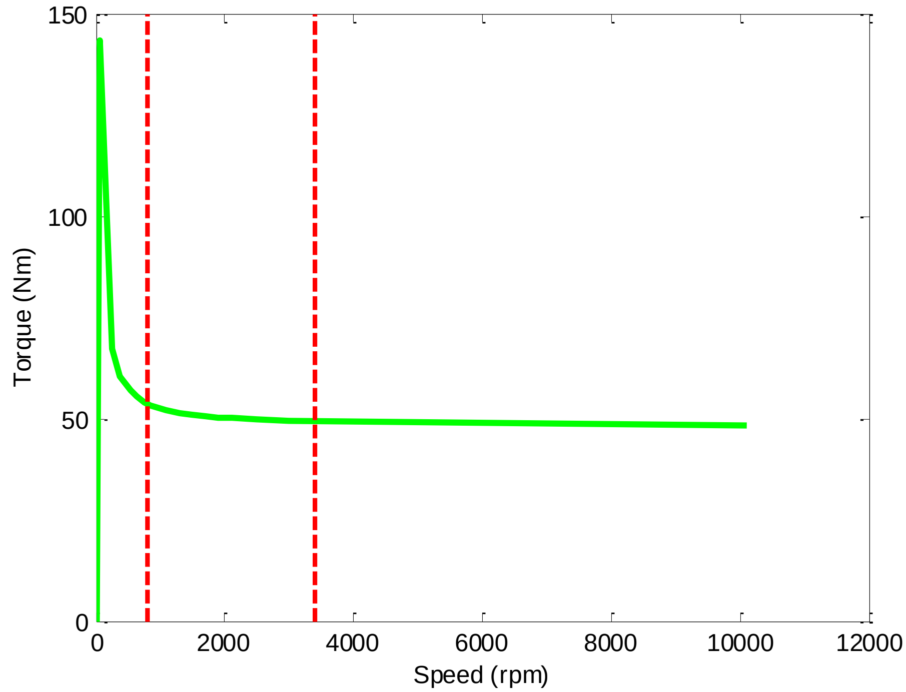

Figure 17- Torque Demand vs Speed for Power Steering

The power steering model uses lookup tables with data from a garbage truck simulator, where the data was originally obtained from SAE (Society of Automotive Engineers) literature [9].The torque demand of the power steering pump is fairly constant within the operating speeds of the engine, so the power demand only scales with the input speed to the power steering unit. Similar to the air compressor, the torque demand spikes at very low speeds. This behavior can be attributed to the increase in friction in the system at very low speeds.

HVAC

The power consumption and therefore torque demand of the HVAC unit is determined by the speed. The torque demand versus speed for the HVAC is shown in Figure 18.

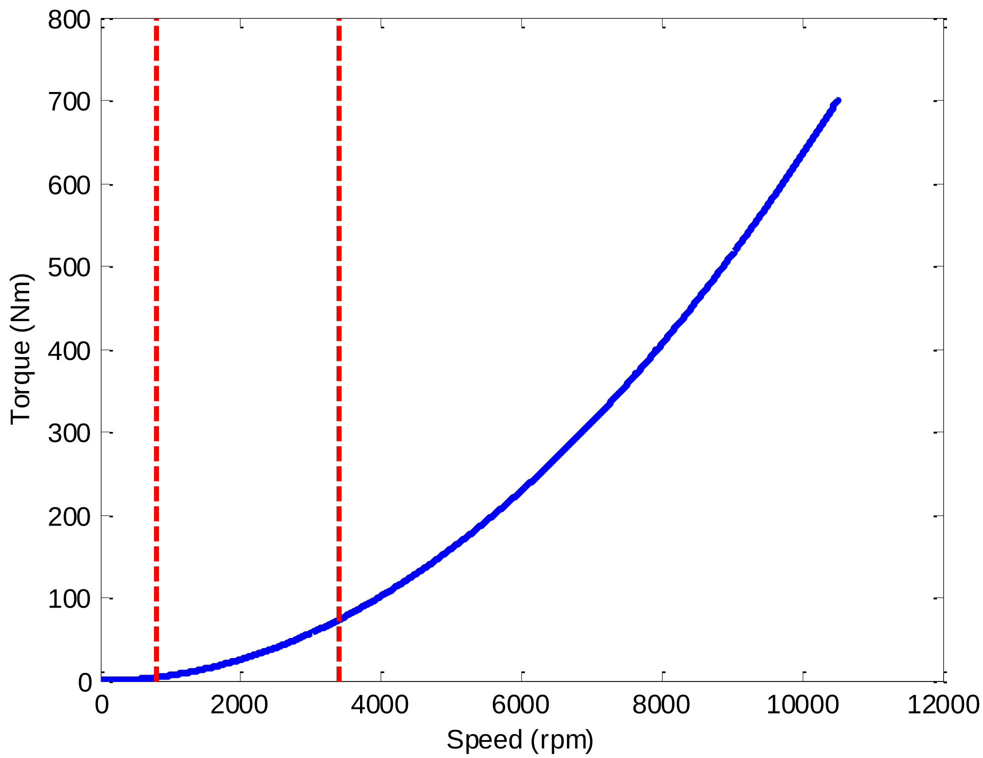

Figure 18- Torque Demand vs Speed for HVAC

The torque demand of the HVAC unit increases quadratically with the input speed. This causes the power demand of the air compressor to be a cubic function, increasing with input speed, shown by Equation 1.

The air conditioning controls the temperature of the cabin. Without developing an accurate model of the cabin temperature, the air conditioning can't be accurately controlled. However, the duty cycle input for the air compressor determines approximately how often the air compressor needs to be turned on, and simulates maintaining a constant cabin temperature.

Power Electronics

The power electronics in the bus transfer one type of electrical energy to another type. These electronics transfer energy very quickly, and are mostly operating at steady state. For this reason, the dynamics of the power electronics for these models are ignored, namely because the transient for the power electronics is significantly faster than that of the other accessories. This allows the model of the power electronics to be a simple gain, which for this thesis is 90% [17] [18].

Comparison

A comparison of the torque demands by different accessories is shown in Figure 19.

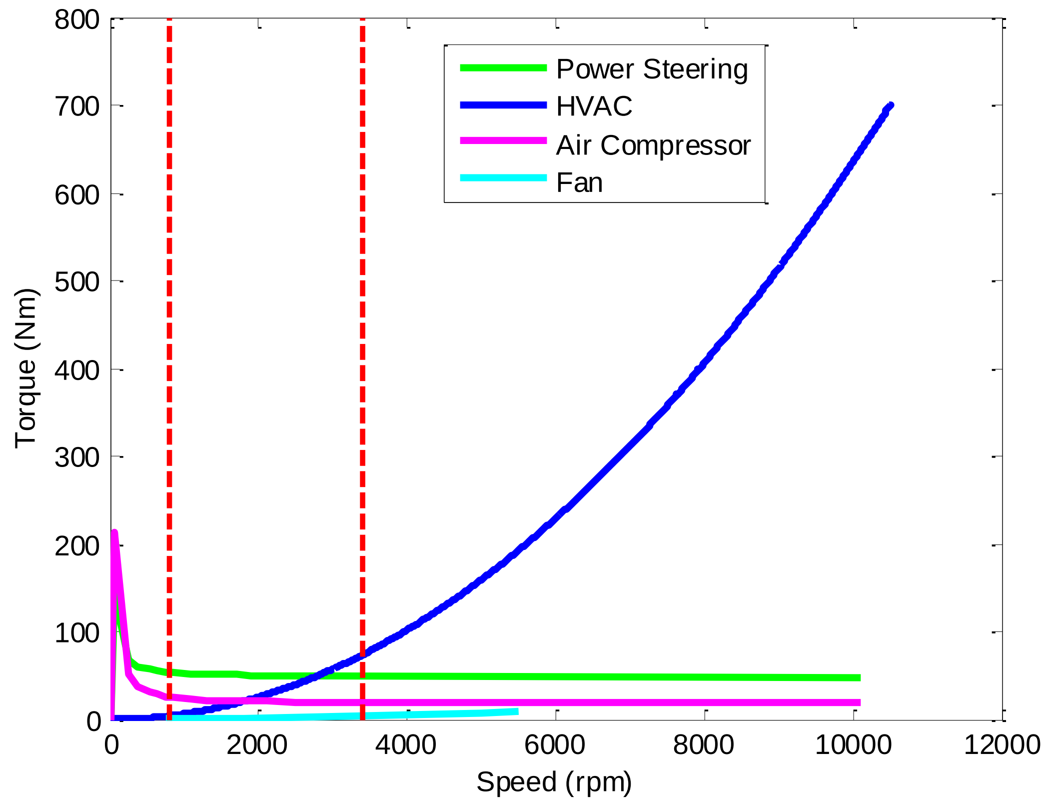

Figure 19- Torque Demand of Accessories

Over the operating range of the engine, the HVAC always request a higher torque than the fan, and the power steering pump always requests a higher torque than the air compressor. At idle speed, the power steering pump demands the highest torque, and the HVAC demands the second lowest amount of torque. However, at the maximum speed of the engine, the HVAC unit demands the highest amount of torque.

CHAPTER 4: SIMULATIONS

4.1 Vehicle Simulator

The simulator of a garbage truck that was previously used was modified to perform as a bus [9]. The refuse loads of the garbage truck were removed, and the vehicle parameters, shown in Table 2, where adjusted to meet those of a bus.

Table 2- Bus Parameters

Vehicle Mass (kg)	Frontal Area (m^2)	Coefficient of Drag (-)	Wheelbase (m)
12636	7.24	0.79	6.85

The vehicle was simulated over a single Manhattan cycle, as shown in Figure 20.

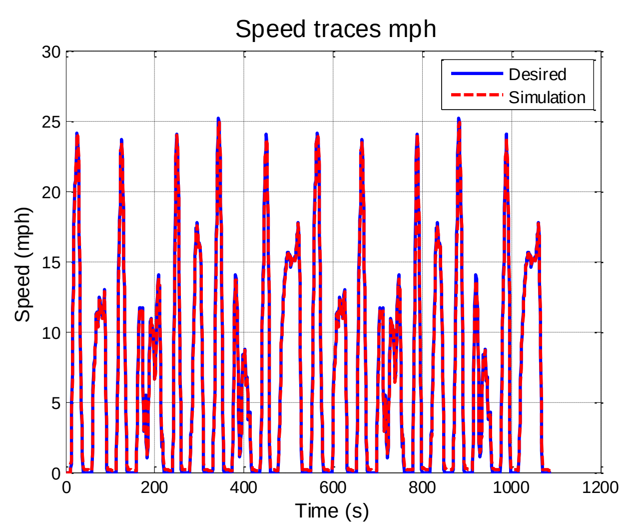

Figure 20- Manhattan Cycle

The Manhattan cycle was developed by studying urban buses in Manhattan, New York. The top speed of the cycle is 25 mph and the average speed is 7 mph. This cycle was chosen because it represents actual routes for transit buses in New York City. The desired speed trace gives the simulated driver an ideal speed, which the simulation tries to match. This speed is the simulation speed, which closely follows the desired speed trace. This is important in terms of the drivability and performance of the vehicle. The vehicle must be able to accelerate or decelerate within reasonable limits, which are set by the drive cycle.

The vehicle speed and therefore engine speed is set by the drive cycle, because the engine is mechanically coupled to the wheels. However, the power demand at the wheels is also a function of the vehicle speed, as shown in Equation 4 [19].

$$P_w = \frac{1}{2}\rho_a C_d A_f V^3 + C_r M_g V + M_{eff} V \frac{dV}{dt} \qquad [4]$$

Where:

ρ_a= Air Density (kg/m^3)

C_d= Coefficient of Drag

A_f= Frontal Area (m^2)

V= Vehicle Velocity (m/s)

C_r= Coefficient of Rolling Resistance

M_g= Vehicle Mass (kg)

M_{eff}= Effective Vehicle Mass (kg)

dV/dt= Vehicle Acceleration (m/s^2)

This equation governs the power that needs to be supplied to the wheels by the engine, as a function of the air resistance, rolling resistance, and change in inertia of the vehicle. The power from the engine goes through the torque converter and transmission, both of which have inefficiencies associated with them. This determines the power that must be supplied to the wheels by the engine. The electrical generator also consumes energy from the engine as well, so the net power demand from the engine is the sum of the power supplied to the wheels of the vehicle and the power supplied to the electrical generator to power the accessory loads.

Regenerative braking is used to recover energy from the wheels, instead of using friction brakes. The regenerative braking scheme used for these simulations takes a percentage of the braking power and uses the electric machine to absorb that power and transform it into electrical energy. When the brake command is activated, the electric machine then consumes the energy that is consumed by friction brakes on a conventional bus. This increases the efficiency of the bus because instead of dissipating excess energy into heat, the bus transforms excess energy into electricity.

4.2 Simulation Results

After the simulations, the results were analyzed. The electric generator’s efficiency map is shown in Figure 21

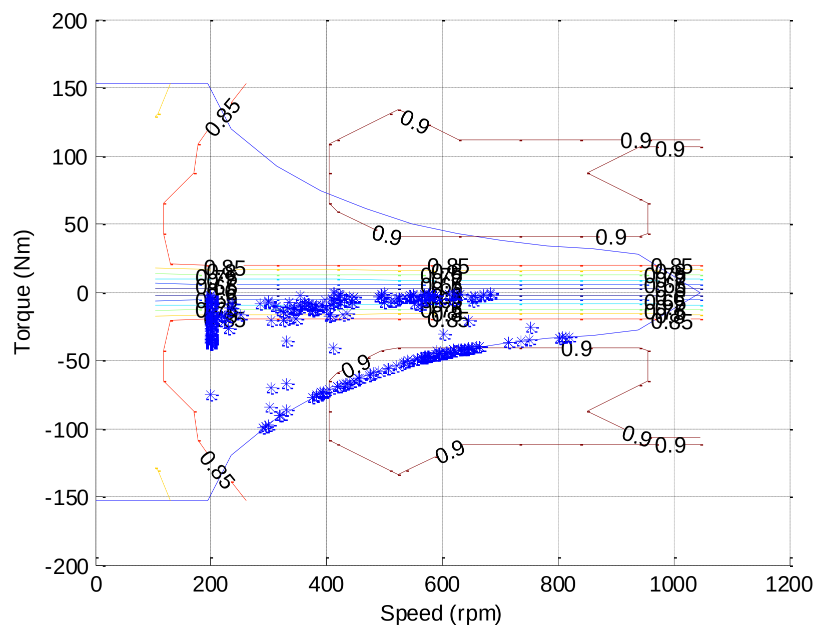

Figure 21- Electric Generator Efficiency Map

All of the operating points of the electric generator are in the negative region of the torque-speed plane. This is because the machine is used solely to generate electricity and not to produce mechanical power. There is a gear train between the electric generator and the engine. This gear train reduces the speed of the electric machine with respect to the engine, which allows the electric machine to operate in more efficient regions on the efficiency map.

The power demanded by the conventional accessories is shown in Figure 22.

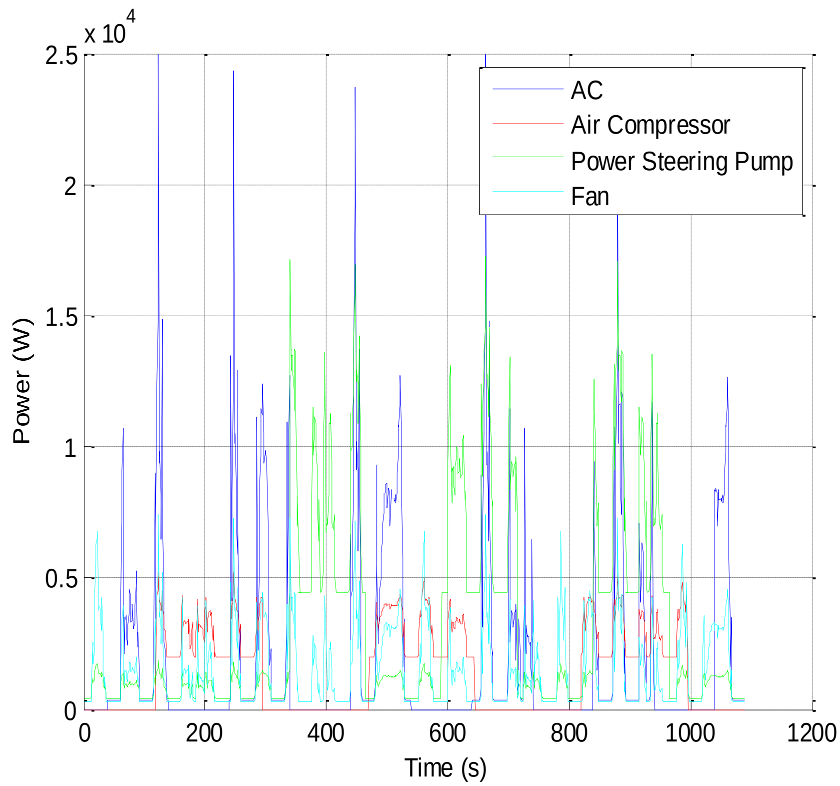

Figure 22- Power Demand from Conventional Accessories

The power demanded by the accessories that were powered directly off the engine fluxuates wildly. This is because the engine speed is variable, and greatly impacts the amount of power that each accessory consumes. The peak power demand by any accessory is 25 kW, demanded by the HVAC. All of the accessories demand at least five kilowatts of power during the high speed portions of the drive cycle. The power demand from the electrified accessories is shown in Figure 23.

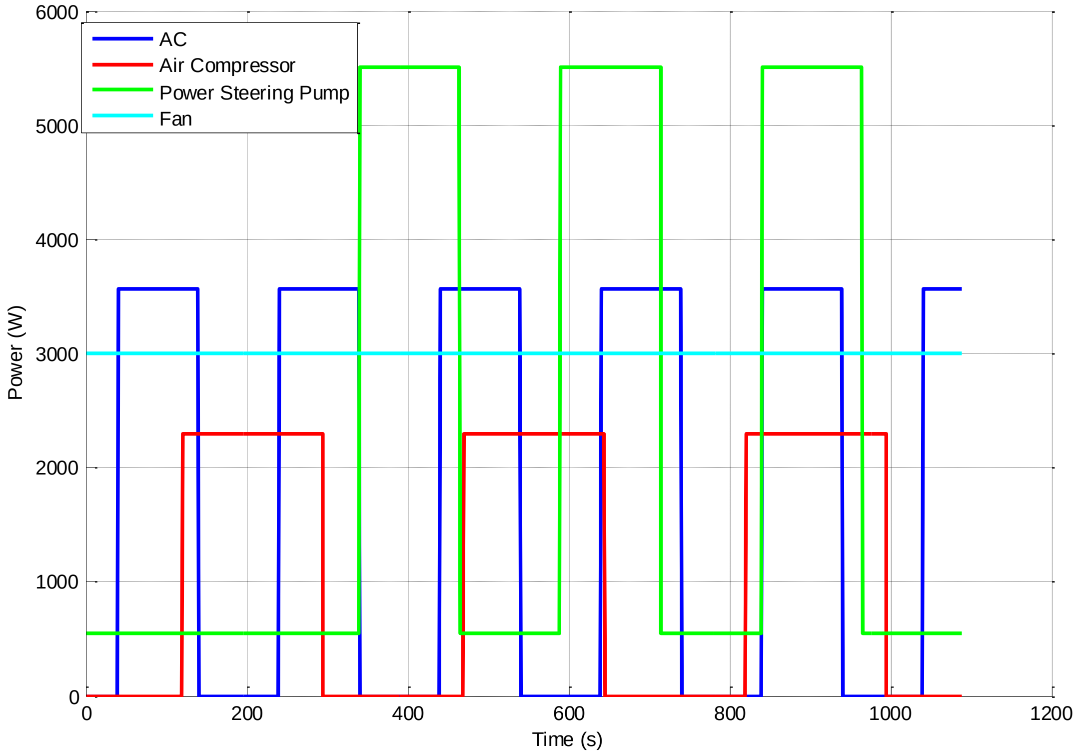

Figure 23- Power Demand from Electrified Accessories

The power demand by the electrified accessories is much more uniform. The maximum power consumed by the HVAC is less than four kilowatts, which is a large decrease from the peak power of 25 kW seen in the conventional accessories. Only one accessory, the power steering pump, consumers more than 5 kW of power. This allows the engine to allocate additional power and torque to the wheels of the vehicle, because it doesn't have to supply as much power to the accessories at high vehicle speeds.

The accessories are run off the battery pack while there is energy in the battery pack. The state of charge of the battery pack as a function of time without utilizing regenerative braking is shown in Figure 24.

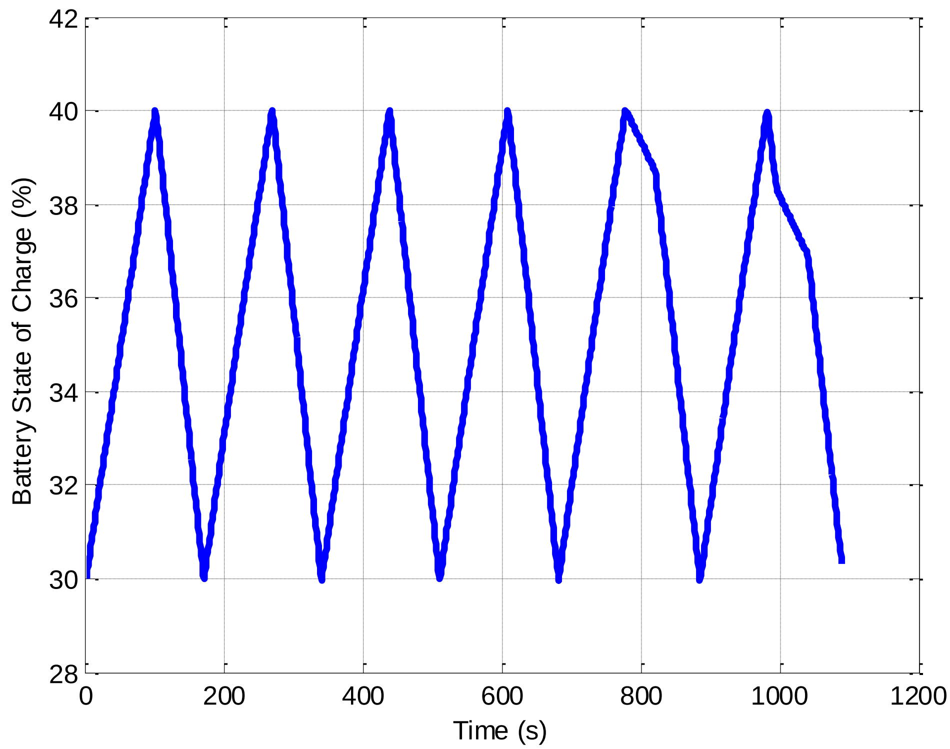

Figure 24- Battery State of Charge without Regenerative Braking

The state of charge of the battery is charge sustaining between 40% and 30%. Only 10% of the total battery state of charge is used, because this powertrain operates in charge sustaining mode. That means that the battery will never be charged be a source external to the vehicle, so the battery must charge while being driven. The battery operates under a control scheme such that when the battery state of charge decreases to 30%, the electric machine supplies its maximum torque at the engine speed to supply energy to the battery and increase its state of charge and to power the accessories. When the battery has 40% state of charge, it depletes by supplying energy to the accessories.

The state of charge of the battery as a function of time for the model that utilizes regenerative braking is shown in Figure 25.

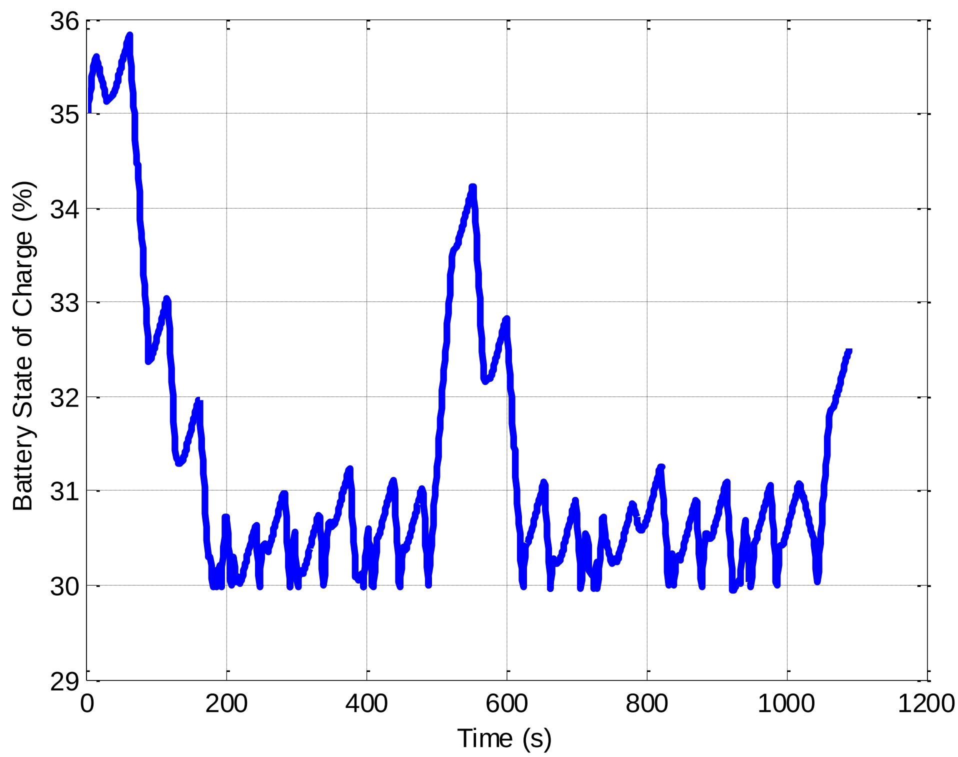

Figure 25- Battery State of Charge with Regenerative Braking

The control scheme changes slightly to allow for regenerative braking. When the brake command is used, the electric generator takes power from the wheels to slow the vehicle down. When this happens, the electrical energy goes to the battery to be stored.

After regenerative braking occurs, the battery goes into charge depleting mode, where energy in the battery is used to power the accessories, until the battery depletes to 30% state of charge. The battery remains charge sustaining for this mode of operation.

The fuel economy for a conventional bus, bus with electrified accessories, and a bus with electrified accessories utilizing regenerative braking is shown in Table 3.

Table 3- Fuel Economy

	Conventional	Electric w/out Regen	Electric w/ Regen
Fuel Consumption (mpg)	2.16	2.17	2.45
% Increase	-	0.5%	13.4%

The conventional bus and the bus with electrified accessories without regenerative braking had similar fuel economies. However, the bus that utilized regenerative braking experienced an increase in fuel economy by 13.4%, which shows that significant increases in fuel economy can be obtained on a bus by electrifying the accessories and implementing regenerative braking.

CHAPTER 5: CONCLUSION

5.1 Significance of Work

The purpose of this research was to develop models of the main accessory loads that are commonly used on buses and determine the effects of electrifying these accessories on the vehicle's fuel economy. Hybrid electric bus powertrains have previously been developed to increase fuel economy, however, these increases come at a large financial price. This study determined that using a smaller electric machine and battery to power the accessory loads produces a significant increase in fuel economy over a drive cycle. The findings from this research show that further development of a bus powertrain architecture that centers on electrified accessories instead of hybridizing the traction system is advantageous from a fuel economy standpoint.

5.2 Future Work

The future of this project is to complete the additional objectives listed in Chapter 2. First, more complete models of accessories need to be developed. These models should include the transient responses of the accessories, because electric accessories can draw significantly higher amounts of current when turning on. This can lead to higher amounts of energy consumed by the accessories than in the simulations if the accessories turn on and off often.

Control schemes also need to be developed for each accessory. Currently, each accessory runs off a duty cycle, which determines whether the accessory is on or off. These duty cycles represent how often each accessory should be on over a drive cycle, but not why the accessory turns on. This means that the energy consumed by each accessory over a cycle is a function of the length of the cycle and nothing else. However, controlling the accessory loads will affect when the accessories are on.

The fan controls the engine temperature. However, to control the engine temperature, the temperature of the engine must first be calculated. To do this, a thermal model of the engine must be developed that can accurately determine the temperature of the engine. After this, the fan control system can be implemented that uses the fan to cool the engine, so the fan only turns on when cooling is required.

Similarly, the HVAC controls the cabin temperature, so to develop a control scheme for the HVAC, an accurate thermal model of the cabin must first be developed. Once the cabin temperature is known, then a control scheme for the HVAC can be developed that sets the cabin temperature to a constant value and only requires the HVAC to turn on when the temperature needs to be changed.

The air compressor controls the pressure in the air tank. But to control the pressure in the tank, the amount of air used from the tank needs to be known, so the pressure in the tank can accurately be calculated. Once this is done, a control scheme for the air compressor can be developed.

The power steering pump controls the pressure in the hydraulic reservoir. The pressure in the reservoir depends on the amount of steering that is done while driving the vehicle. Once the pressure in the reservoir is determined, a control system for the power steering pump can be developed.

The battery that is currently in the simulator is a high voltage battery. The powertrain architecture calls for a smaller, 24 volt battery, so this model will have to be developed. This will impact the control scheme because far less electrical energy will be able to be stored on the vehicle. This means that capturing all of the regenerative braking energy will be challenging, as well as supplying power to the accessories when the engine cannot supply sufficient energy.

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